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FEASIBILITY OF UNDERWATER FRICTION STIR WELDING OF HY-80 STEEL

by

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March 2011

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The purpose of this thesis is to determine the feasibility of underwater friction stir welding (FSW) of high-strength; quench and temper low carbon steels that are susceptible to hydrogen-assisted cracking (HAC). The specific benefits of underwater FSW would be weld repairs of ship and submarine control surfaces and hulls without the need for dry-docking and extensive environmental control procedures. A single tool of polycrystalline cubic boron nitride (PCBN) in a Tungsten-Rhenium binder was used to conduct three bead-on-plate FSW traverses, approximately 40 inches in length on 0.25 inch HY-80 steel. The first traverse was a dry weld and the second and third traverse were wet (underwater) welds, all conducted at a combination of 400 revolutions per minute and 2 inches per minute. The wet welds were conducted for the purpose of assessing the HAC susceptibility of the process.

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FEASIBILITY OF UNDERWATER FRICTION STIR WELDING OF HY-80 STEEL

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ABSTRACT

The purpose of this thesis is to determine the feasibility of underwater friction stir welding (FSW) of high-strength, quench and temper low carbon steels that are susceptible to hydrogen-assisted cracking (HAC). The specific benefits of underwater FSW would be weld repairs of ship and submarine control surfaces and hulls without the need for dry-docking and extensive environmental control procedures. A single tool of polycrystalline cubic boron nitride (PCBN) in a Tungsten-Rhenium binder was used to conduct three bead-on-plate FSW traverses, approximately 40 inches in length on 0.25 inch HY-80 steel. The first traverse was a dry weld and the second and third traverse were wet (underwater) welds, all conducted at a combination of 400 revolutions per minute and 2 inches per minute. The wet welds were conducted for the purpose of assessing the HAC susceptibility of the process.

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LIST OF ACRONYMS AND ABBREVIATIONS

BM – Base Material

CNC – Computer Numerical Controlled

FSP – Friction Stir Processing

FSW – Friction Stir Welding

FSW/P – Friction Stir Welding and/or Processing

HAC – Hydrogen Assisted Cracking

HAZ – Heat Affected Zone

IPM – Inches per Minute

NPS – Naval Postgraduate School

PCBN – Polycrystalline Cubic Boron Nitride

RPM – Rotations per Minute

SEM – Scanning Electron Microscope

SZ – Stir Zone

TMAZ – Thermo-Mechanically Affected Zone

USN – United States Navy

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I. INTRODUCTION

High strength low alloy steels such as HY-80 and HY-100 are used in the quenched and tempered condition for several applications in the US Navy, especially in ship hulls, and extensive welding is carried out in both fabrication as well as repair. The strengthening of high-strength steels by martensitic transformation leaves these alloys susceptible to Hydrogen Assisted Cracking (HAC) [1]. As a result of this susceptibility, welding these metals requires extensive preparations including, among others, pre- and post-heating, filler electrode controls such as baking and storage, and control of moisture and hydrocarbons. Welding high-strength steels underwater is difficult and requires extensive and expensive additional preparations involving such special techniques, equipment and highly specialized training adding to the cost and time of repairs [2].

Los Angeles class submarines have had fatigue cracking on the control surfaces and the difficulty in welding high-strength steels requires drydocking the submarine to make repairs. Maintaining the necessary environmental controls in a drydock is difficult due to the seawater trapped inside of the control surfaces. Putting a submarine in drydock costs the Navy and taxpayers hundreds of thousands of dollars annually.

Friction stir welding (FSW) and processing (FSP) are solid state processes used in the joining and processing of metals. Friction stir welding and processing have been used on the Littoral Combat Ship (LCS) and the processing of nickel aluminum bronze propellers used on Navy ships and submarines. Friction stir welding is accomplished by using a cylindrical, rotating tool with a shoulder and projecting pin in pressed into the surface of the abutting edges of the materials to be welded. The material is softened enough for the tool pin to plunge into the material until the shoulder contacts the surface via frictional and adiabatic heating. The tool traverses along the weld line to produce a weld through the severe plastic deformation in the stir zone. Figure 1 illustrates the basic FSW/P nomenclature. Numerous studies have been conducted on the friction stir welding effects of hardenable alloy steels but, to date, very few studies have been

conducted on underwater friction stir welding, except for the recent NPS thesis work by Lieutenant Norman Overfield (NPS Thesis, December 2010).

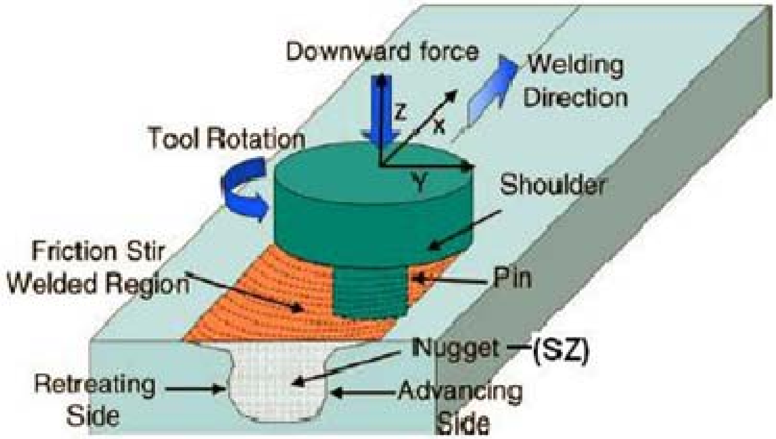

Figure 1. FSW/P Nomenclature. After [3]

Friction stir welding and processing were invented by The Welding Institute in Cambridge, United Kingdom in 1991. However, most advances have been accomplished in more recent years due to the limitations of materials available for the tool. FSW/P will become more economical as more advances are made in the tool, robust and portable equipment, techniques. However, friction stir welding and processing will likely not replace traditional methods for welding most steels. It will likely be used in niche applications.

Since friction stir welding and processing is conducted below the melting point of the material, hydrogen solubility will be reduced and hydrogen resulting from decomposition of water during FSW/P is not expected. As a result, FSW could be used to produce defect-free welds in hardenable alloy steels underwater and be economically beneficial.

II. BACKGROUND

As tool materials and designs advance, studies on friction stir welding and processing have steadily increased. Experiments on steels from ultralow carbon to ultrahigh carbon content [4, 5] have yielded defect free welds. Defect free welds have also been produced in specialized steels including DP980 (advanced high strength steel) [6] and SKD61 tool steel [7].

The chemical composition and tool parameters such as tool RPM, traversing IPM and normal force determine the microstructure of friction stir welded or processed material. In studies conducted, defect free welds have been produced using tool and traverse speed parameters ranging from 1000 RPM and 15 millimeters per second (35 IPM) [8] to 100 RPM and 25 millimeters per minute (1 IPM) [9]. Normal force data is incomplete; however, they tend to range from 5kN (1124 lbf) [8] to 40kN (9000 lbf) [10]. As a result of studies so far, each specific type of steel will require additionally studies to determine its own set of parameters and tolerances required to produce a defect free weld, as long as the weld is conducted within the set standards.

A martensitic microstructure was produced in the stir zone and TMAZ, on a smaller scale, in most cases. In these cases, the temperature in the stir zone exceeded α_1 (temperature at which complete austenite forms) during the processing, therefore rapidly cooled, and formed martensite. One study produced martensite free welds by controlling the friction stir welding parameters which prevented the stir zone temperature from exceeding α_1 [11]. As a result of these studies, post-weld metallurgical properties can be controlled by controlling the friction stir welding or processing parameters. Therefore, these parameters can be modified to suit a wide range of applications and eliminate pre- and/or post-weld heat treatments.

So far, studies evaluating the feasibility of FSW/P underwater are extremely limited. Underwater welding requires unique skills and equipment not normally available to a shipyard welder using conventional fusion welding techniques. This results in increased cost and time. U.S. Navy shipyards do not typically employ qualified

underwater welders. Also, industry standards for underwater welding of HY-80 or HY-100 steels do not exist [12]. HY-80 and HY-100 alloys involve heat treating to produce tempered martensitic microstructures. As a result, these materials are susceptible to hydrogen assisted cracking. The potential of FSW/P to prevent HAC in hardenable steel alloys is the basis for this and future research. Additionally, FSW/P of HY-80 and similar steels could result in significant cost savings by eliminating the need for a dry dock to complete submarine repairs. This study was initiated to compare previous results obtained by LT Norman Overfield to FSW of HY-80 steel. HY-80 steel was obtained and a comparative study of 4142 steel to HY-80 steel was conducted to understand the influence of chemical composition on the resulting microstructures and mechanical properties.

III. EXPERIMENTAL PROCEDURE

A. MATERIAL PROCESSING

A steel plate was obtained from the Naval Surface Warfare Center – Carderock Division, Bethesda, MD, that was 0.25 inches (6.4mm) thick and 26.5 inches (mm) wide by 43.5 inches (mm) long. Pre-welding chemical analysis was conducted by Anamet, Inc., Hayward, CA and confirmed the material conformed to the HY-80 steel specification. The plate was cut into three sections for base metal analysis and dry and wet (underwater) friction stir processing and for future research. Each plate measured approximately 26.5 inches (mm) long by 14.5 inches (mm) wide. One plate was sectioned to produce 25 Charpy V-notch samples and 5 tensile test samples each in both the rolled and transverse directions. The second plate was cut into two sections each measuring approximately 26.5 inches (mm) by 7.25 inches (mm). One section each was used for dry and wet (underwater) FSP. Initially, the plate was sand blasted to remove mill-scale. However, following the dry friction stir weld, the second plate was hand-ground to be sure all mill-scale was removed. All FSW was performed parallel to the long dimension [13]. The FSP was conducted by Advanced Metal Products and MegaStir Technologies in Provo, Utah. Figure 2 is the underwater friction stir welding chamber. It is made from clear plexiglass to enable clear observation of the FSW/P process. A copper cooling coil is attached to a chiller to provide heat removal of the water and prevent the salt water from boiling off. The chamber is sealed to plate using silicone adhesive. The water in the chamber is saltwater (3.5% salt content).

Figure 2. Underwater chamber with cooling coil for FSW/P. From [13]

A dry FSP run of approximately 25 inches was completed at 400 RPM and 2 IPM. A plunge load of greater than 15,000 pounds was applied and decreased to 10,000 pounds. A software error caused the tool to extract after a few inches of weld, requiring a second plunge and traverse (Figure 3) [13]. Following the second plunge, the first 12 inches of weld surface looked good. There were, however, occasional surface flaws on the advancing side that may have been caused by surface oxides or mill-scale but further study is required to determine the exact cause (Figure 4). As the weld progressed, the surface flaws became more pronounced and severe. In the final 10 inches of the weld run, severe lack of bonding on the advancing side is visible (Figure 5) [13]. As a result, the tool was moved to a parallel location and an attempt was made using different approaches to produce a defect free weld including improved surface preparation and different FSW parameters (Figure 6). The severe defects remained but weld flash was reduced with improved surface finishing.

Figure 3. Dry FSW second plunge and traverse. From [13]

Figure 4. Shallow surface defects on the tool advancing side of dry FSW. From [13]

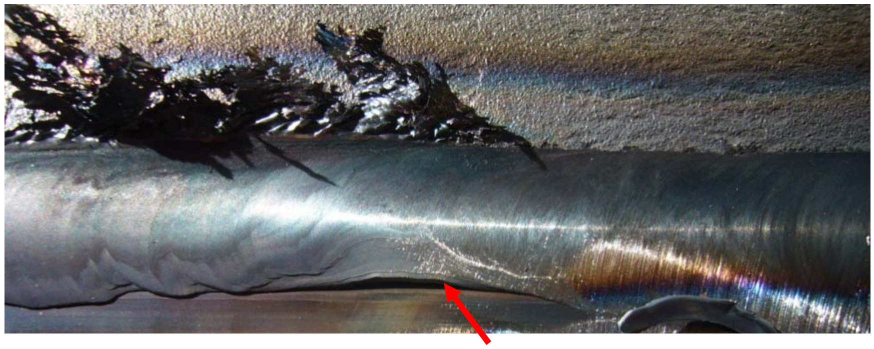

Figure 5. Lack of bonding on advancing of last 10 inches of weld length. From [13]

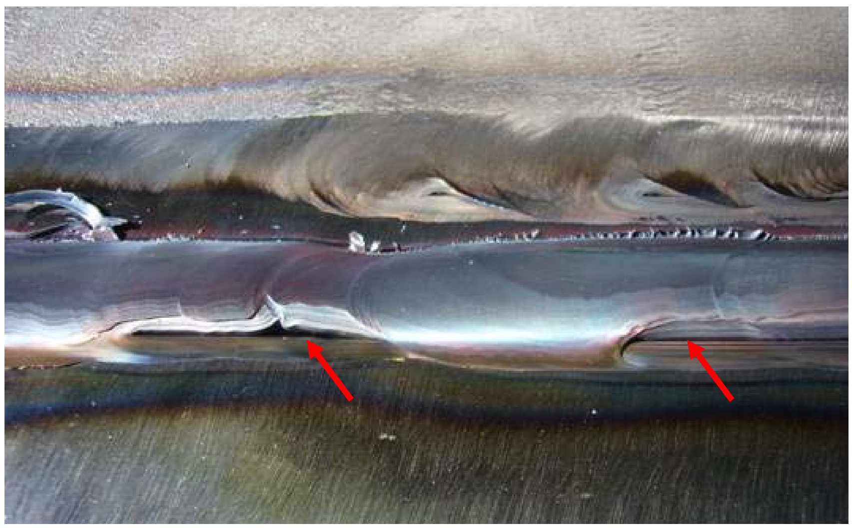

Figure 6. Attempts at defect free weld runs by improving surface finish and changing FSW parameters. Advancing side defect remained but weld flash eliminated. From [13]

The tool material was polycrystalline cubic boron nitride (pcbn) consolidated with a metallic binder identified as MS80. The tool design was a convex scroll shoulder with a step spiral pin (CS4) (Figure 7) [13].

Figure 7. Polycrystalline cubic boron nitride (PCBN) CS4 tool used for FSW. From [13]

Due to the size limitations of the underwater chamber, two approximately 10 inch underwater weld runs were completed for a total length of approximately 20 inches. Figure 8 shows the underwater weld setup in progress. Figure 9 shows a relatively good surface appearance for the first weld. A small amount of weld flash and surface oxidation is visible but the weld appears to be free of defects and full penetration. Figure 10 shows the weld root surface and the tool extraction site [13]. Underwater welding was carried out in water containing 3.5wy% NaCl in order to simulate the welding in seawater.

Figure 8. Underwater FSW in progress. From [13]

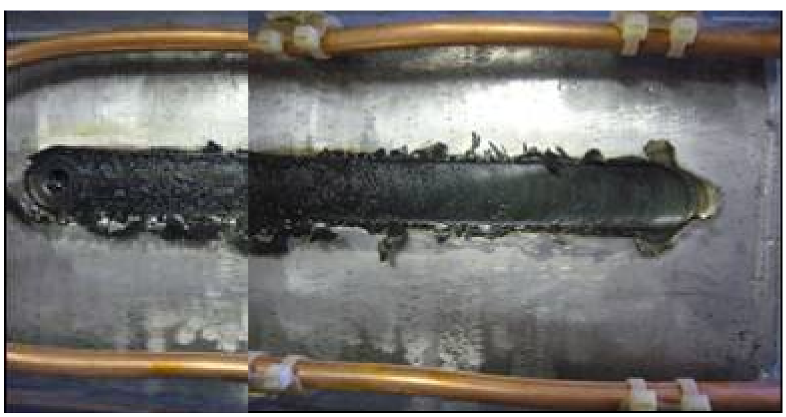

Figure 9. Surface appearance of first underwater FSW run. From [13]

Figure 10. Root surface of underwater friction stir weld. From [13]

For the second underwater FSW run, the chamber was moved to the other half of the plate and resealed. During the second FSW, a leaked occurred and all of the water drained from the chamber. The chamber was refilled with fresh tap water and the weld was finished [13]. Figure 11 shows the weld surface of the second wet FSW [13].

Figure 11. Second underwater FSW. From [13]

B. CHEMICAL TESTING

Anamet, Inc. performed chemical testing on the base material to verify that the material was HY-80 steel and to establish a baseline to which future chemical testing of FSW/P material can be compared. Anamet, Inc. determined that the material was in fact HY-80 steel [14] based on their chemical analysis.

C. MICROSTRUCTURE ANALYSIS

1. Specimen Preparation

Figure 12 represents how the unprocessed samples were machined out of the plate. Samples were prepared using standard processes and final polishing was performed using a 0.5 micron Al_2O_3 suspension. The prepared surfaces were etch using a 5% Nital etchant (5% HNO_3 – 95% Methanol).

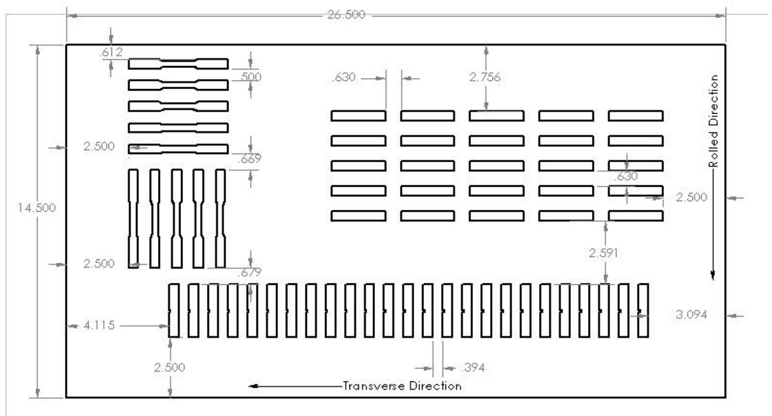

Figure 12. Machining layout

2. Optical Microscope Imaging

An optical microscope was used to examine the specimens under various magnifications. Several locations were viewed such as BM, TMAZ (advancing side), and SZ. Low-magnification montages were developed to show the entire width of the SZ, left and right TMAZ, as well as BM on either side.

3. SEM Imaging

A Ziess NEON40 SEM was used with field emission electron source operating at 15 keV to examine the specimens under various magnifications. The results from several locations are noted in Chapter IV.

D. MECHANICAL TESTING

1. Microhardness

A HVS-1000 digital microhardness tester was used to micro-indent each specimen to establish a Vickers hardness profile in a grid pattern (Figure 13).

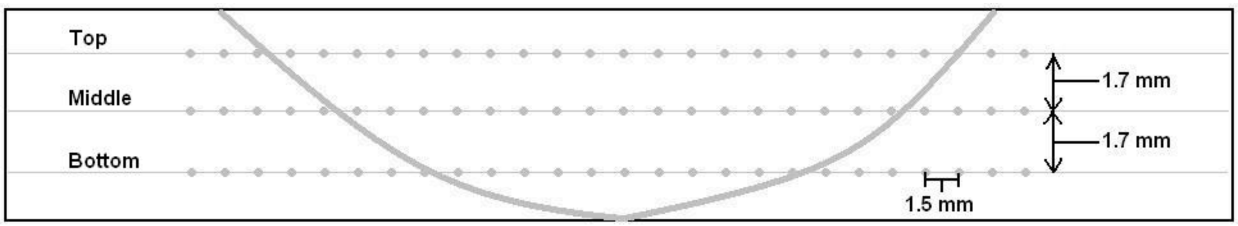

Figure 13. Illustration of the Vickers hardness grid pattern. Gray line represents nominal stir zone shape.

A test load of 9.8 N with a 15 sec pause was used with a loading and unloading rate of 20 N/min.

2. Charpy V-Notch

a. Specimen Preparation

Charpy V-Notch test specimens were machined from the base material plate using a band saw and finished with a CNC machine to ASTM standards [15]. Figure 14 represents the Charpy V-Notch. Twenty-five samples were made in break in the rolled direction and 25 samples were made to break in the transverse direction.

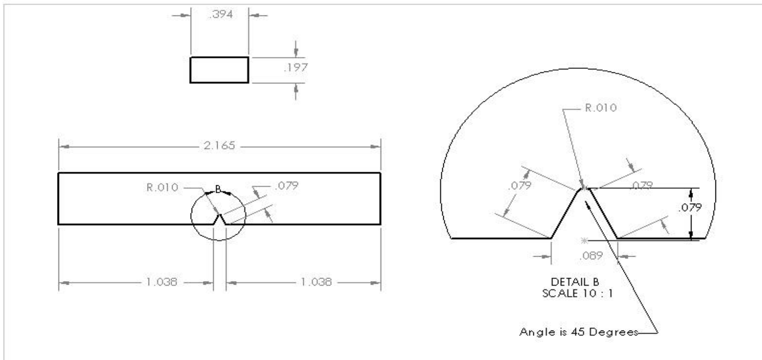

Figure 14. Charpy V-Notch test sample. From [15]

b. *Specimen Testing*

The Charpy V-Notch test was conducted using at varying temperatures ranging from approximately -200°C (Liquid Nitrogen) to 21.5°C (ambient room temperature). Low temperature tests were carried out at ice (0°C), iced saturated salt-water mixture (~ - 20°C) liquid nitrogen-cooled methanol (~ -55°C) and liquid nitrogen (-196°C)

3. Tensile

a. *Specimen Preparation*

Tensile test specimens were machined from the three different sections using a band saw and finished with a CNC machine to ASTM standards [16]. Figure 15 represents the tensile test samples. Five samples were made to break in the rolled direction, and five samples were made to break in the transverse direction.

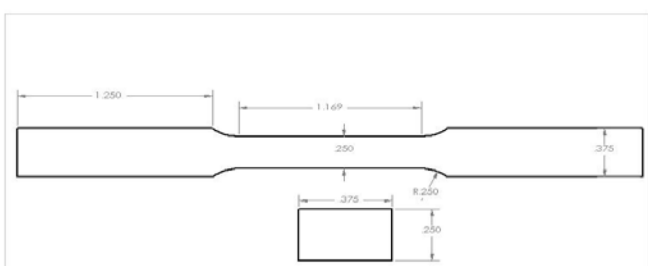

Figure 15. Tensile test sample. From [16]

b. Specimen Testing

Tensile testing was conducted using eight tensile test specimens machined from the base material plate. Four specimens were cut longitudinally with the rolled direction and four specimens were cut transverse to the rolled direction. All tensile tests were conducted using a strain rate of 2.1×10^{-3} per second. The results are discussed in Chapter IV.

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IV. RESULTS AND DISCUSSION

A. VISUAL INSPECTION

Surface defects are readily apparent in the dry FSW. As shown previously in Figures 3–7, there is significant weld flash and lack of bonding on the advancing side of the weld. The wet FSW runs appear to be defect free ad fully penetrated welds with the exception of minor weld flash.

B. CHEMICAL ANALYSIS

The testing done by Anamet, Inc. concluded that the base material has a similar chemical composition to HY-80 steel. Table 1 shows the measured and required chemical composition of HY-80 steel. Table 2 compares the chemical compositions of the HY-80 and the HY-100 steels and it can be seen that the two steels are nearly identical in chemical composition and thus difficult to distinguish by chemical analysis alone.

SPECTROCHEMICAL ANALYSIS (Reported as WT%)				REQUIREMENTS Ultra Service Steel (USS HY-80)	
				Min	Max
Carbon	(C)	0.167		---	0.18
Chromium	(Cr)	1.52		1.00	1.8
Copper	(Cu)	0.09		---	0.25
Manganese	(Mn)	0.39		0.10	0.40
Molybdenum	(Mo)	0.24		0.20	0.60
Nickel	(Ni)	2.33		2.00	3.25
Phosphorous	(P)	0.015		---	0.025*
Silicon	(Si)	0.24		0.15	0.35
Sulfur	(S)	0.015		---	0.025*
Titanium	(Ti)	<0.005		---	0.02
Vanadium	(V)	0.01		---	0.03

*P + S = 0.045 Max

Table 1. Measured and required chemical composition of HY-80 steel. After [14]

		HY-80		HY-100	
Density		7.87 g/cc	0.284 lb/in³	7.87 g/cc	0.284 lb/in³
Tensile Strength, Yield		>=552 Mpa	>= 80000psi	>= 689 Mpa	>= 100000 psi
Modulus of Elasticity		205 Gpa	29700 ksi	205 Gpa	29700 ksi
Poissons Ratio		0.280	0.280	0.280	0.280
Shear Modulus		80.0 Gpa	11600 ksi	80.0 Gpa	11600 ksi
Compostion (WT%)		Min	Max	Min	Max
Carbon	(C)	0.12	0.18	0.12	0.20
Chromium	(Cr)	1.00	1.80	1.00	1.80
Copper	(Cu)	---	0.25	---	0.25
Iron	(Fe)	93.1	96.4	92.8	96.2
Manganese	(Mn)	0.10	0.40	0.10	0.40
Molybdenum	(Mo)	0.20	0.60	0.20	0.60
Nickel	(Ni)	2.00	3.25	2.25	3.50
Phosphorous	(P)	---	0.025*	---	0.25
Silicon	(Si)	0.15	0.35	0.15	0.35
Sulfur	(S)	---	0.025*	---	0.025
Titanium	(Ti)	---	0.020	---	0.020
Vanadium	(V)	---	0.030	---	0.030
*P + S = 0.045 Max					

Table 2. Comparison of HY-80 to HY-100 steel

C. OPTICAL MICROSCOPY

In the base material, lighter and darker bands parallel to the plane of the rolled sheet were visible (Figure 16). This indicates that the thermomechanical processing did not completely homogenized the material by removing all remnants of segregation and coring effects. The microstructure is suggestive of a ferritic–pearlitic structure in lower strength steels and the final heat treatment to produce a tempered martensitic structure evidently did not remove these effects.

Figure 16. Base material at 2.5x. A band-like distribution is visible.

The dry stir zone appears to be narrower than the wet stir zone. The wet TMAZ appears to be narrower than the dry TMAZ. This likely caused by the higher quenching rate of the wet FSW. The wet stir zone appears to be more homogenized as well.

Figure 17. Montage of micrographs of dry FSW at 2.5x

Figure 18. Montage of micrographs of wet FSW at 2.5x

At the low magnification (Figure 19), the “flow bands” are more visible in the dry TMAZ. The wet TMAZ is narrower than the dry TMAZ. Additionally, the layering of ferrite and pearlite is still visible close to the TMAZ in both samples.

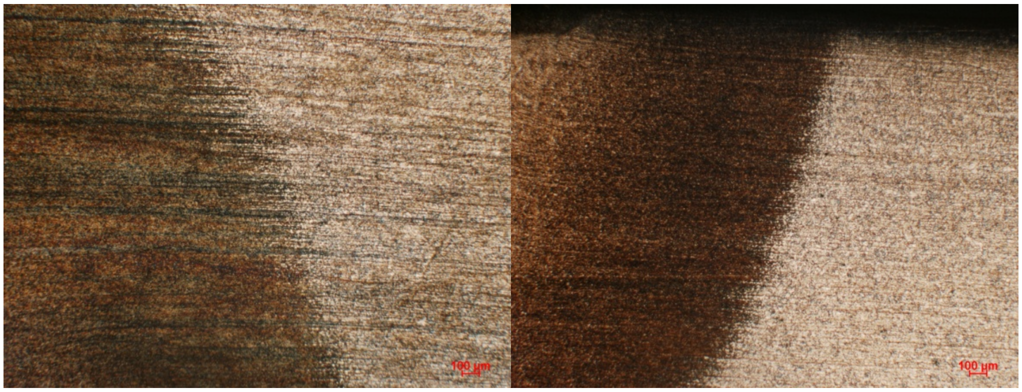


Figure 19. Micrographs of the TMAZ at 2.5x magnification: Dry (l) and Wet (r)

At a higher magnification (Figure 20), the layering of pearlite and ferrite is more apparent as well as the “flow bands” in both samples.

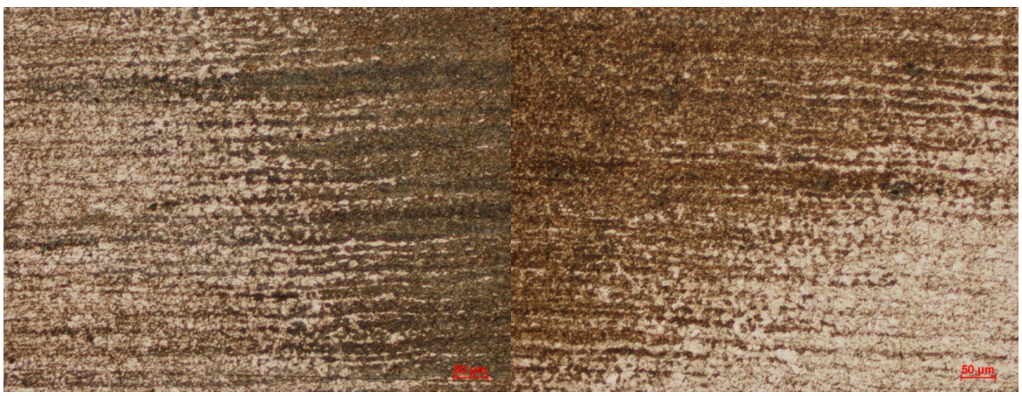


Figure 20. Micrographs of the TMAZ at 10x magnification: Dry (l) and Wet (r)

At high magnification, the stir zones appear similar but the wet stir zone appears more homogenized than dry stir zone. When compared to the base material both samples exhibit significant homogenization. Under the optical microscope, it is difficult to tell whether the microstructure is martensitic or bainitic. This will be discussed later with the scanning electron microscope results.

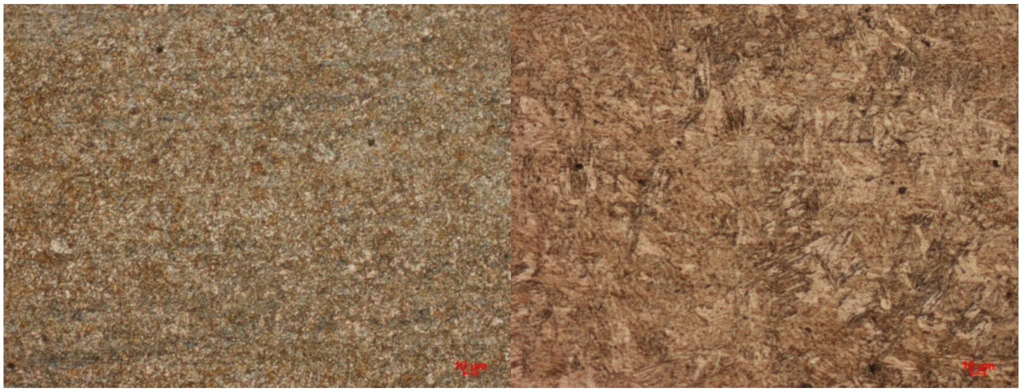


Figure 21. Micrograph of the stir zone at 20x magnification: Dry (l) and Wet (r)

There does not appear to be any tunneling defects or any other major defects in either stir zone.

D. SEM MICROSCOPY

Micrographs of the base material, TMAZ and stir zones, for both dry and wet FSW, were taken using the scanning electron microscope (SEM). It was clear that the microstructure developed as result of the FSW an untempered martensite. The homogenization of the stir zone compared to the base material was even more apparent with the SEM.

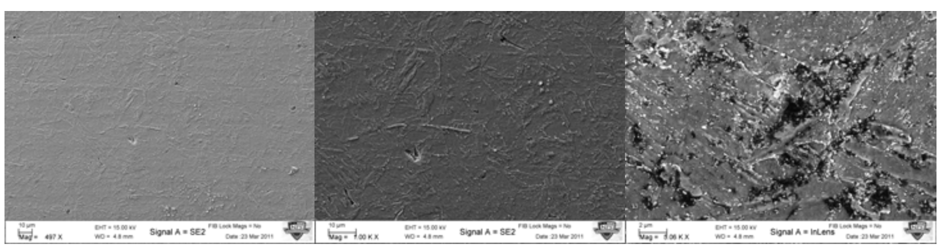


Figure 22. SEM Micrographs at various magnifications: (l to r) 500x, 1000x, and 5000

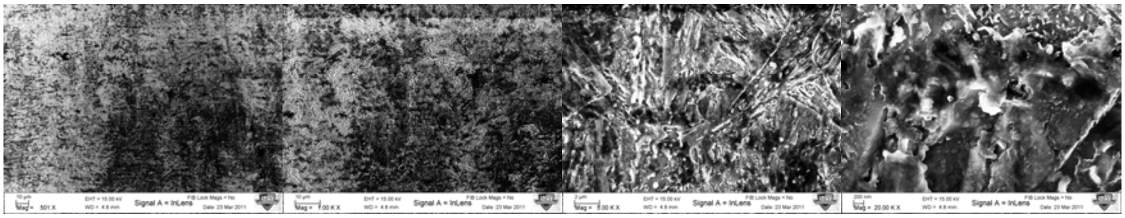


Figure 23. Dry FSW TMAZ SEM Micrographs at various magnifications: (l to r) 500x, 1000x, 5000x, 20,000x.

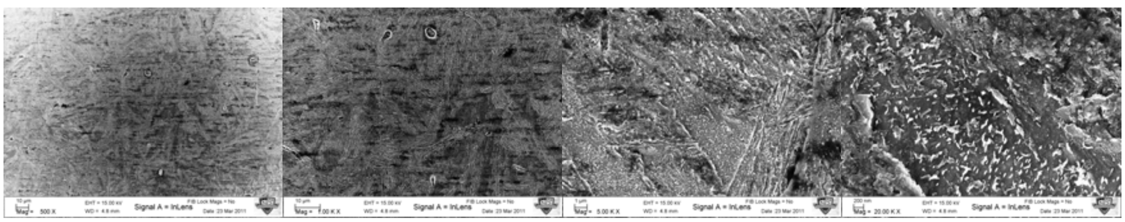


Figure 24. Dry FSW Stir Zone SEM Micrographs at various magnifications: (l to r) 500x, 1000x, 5000x, 20,000x.

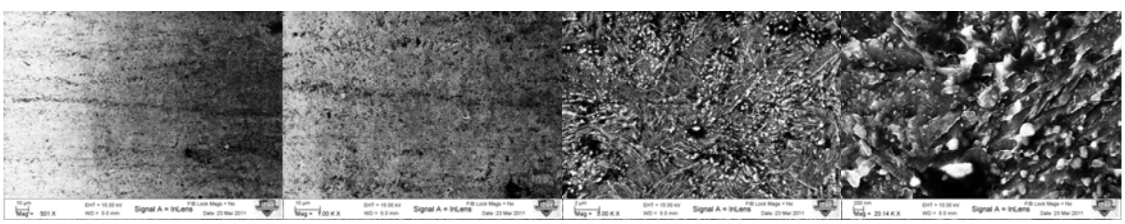


Figure 25. Wet FSW TMAZ SEM Micrographs at various magnifications: (l to r) 500x, 1000x, 5000x, 20,000x.

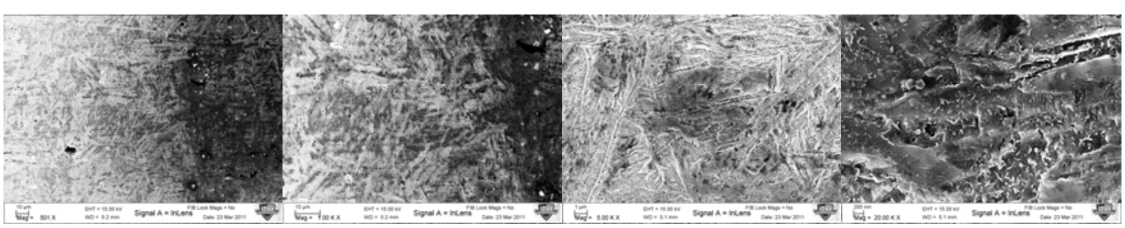


Figure 26. Wet FSW stir zone SEM Micrographs at various magnifications: (l to r) 500x, 1000x, 5000x, 20,000x

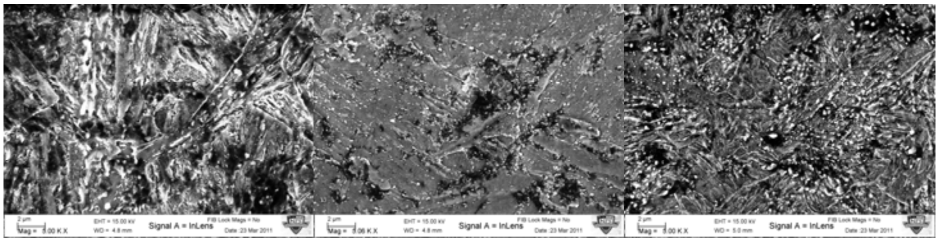


Figure 27. Comparison of SEM Micrographs at 5000x: (l to r) Dry TMAZ, BM, Wet TMAZ.

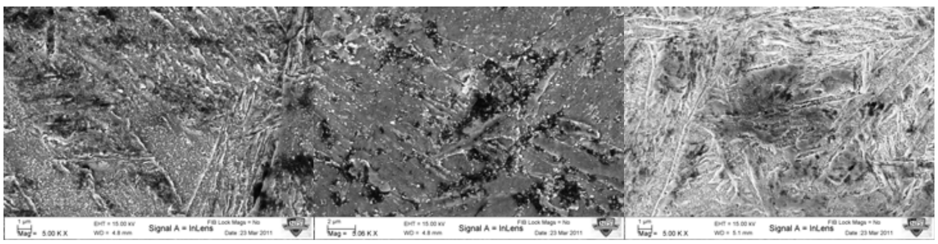


Figure 28. Comparison of SEM Micrographs at 5000x: Dry SZ, BM, Wet SZ.

It is apparent from the SEM micrographs that there is significant change in the microstructure between the base and the stir zone and even the dry FSW and wet FSW. The wet stir zone and TMAZ show smaller grains than the dry stir zone and base material.

E. MECHANICAL PROPERTIES

The mechanical properties of the base material were evaluated by Vickers hardness, Charpy V-Notch impact test and the tensile test. The processed material was evaluated by Vickers hardness test. The Vickers hardness was taken across the stir zone at various depths from the sample surface.

1. Microhardness

Vickers hardness values of the base material ranged from 224 to 272. This is likely due to inhomogeneous material as previously discussed (including porosity, inclusion and the layering of ferrite and pearlite present.

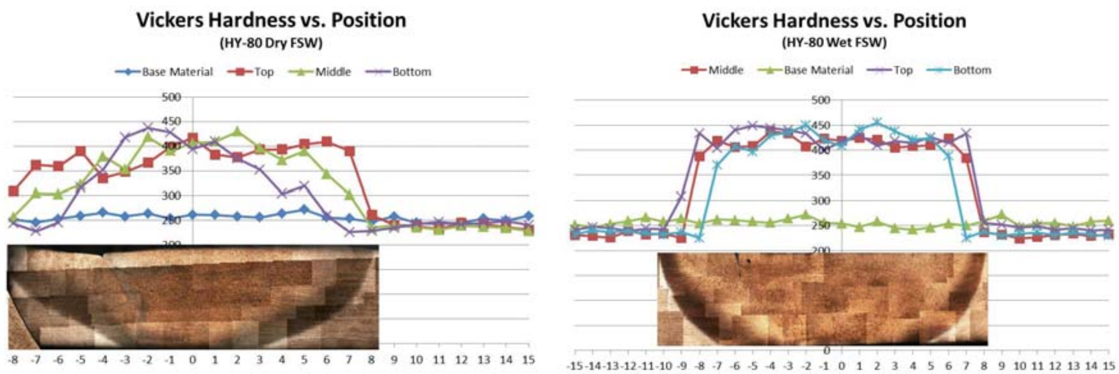


Figure 29. Microhardness data for Dry and Wet FSW

From this data, there is significant hardening in the TMAZ and stir zone over the base material. This requires further research but most likely reflects martensitic transformation after FSW with insufficient time during cooling to produce tempering. The hardness across the wet FSW is more consistent. This may due to overlapping FSW runs.

2. Charpy V-Notch Impact Test

Charpy V-Notch Impact testing was done to determine the Ductile-to-Brittle Transition Temperature (DBTT) of the base material to establish a baseline to compare the processed material. Charpy V-Notch test revealed that our DBTT is between -192°C and -54.5°C. DBTT below -50°C is desired as it will be outside of the operating temperature of U.S. Navy ships and submarines. The figure below shows the data in more detail.

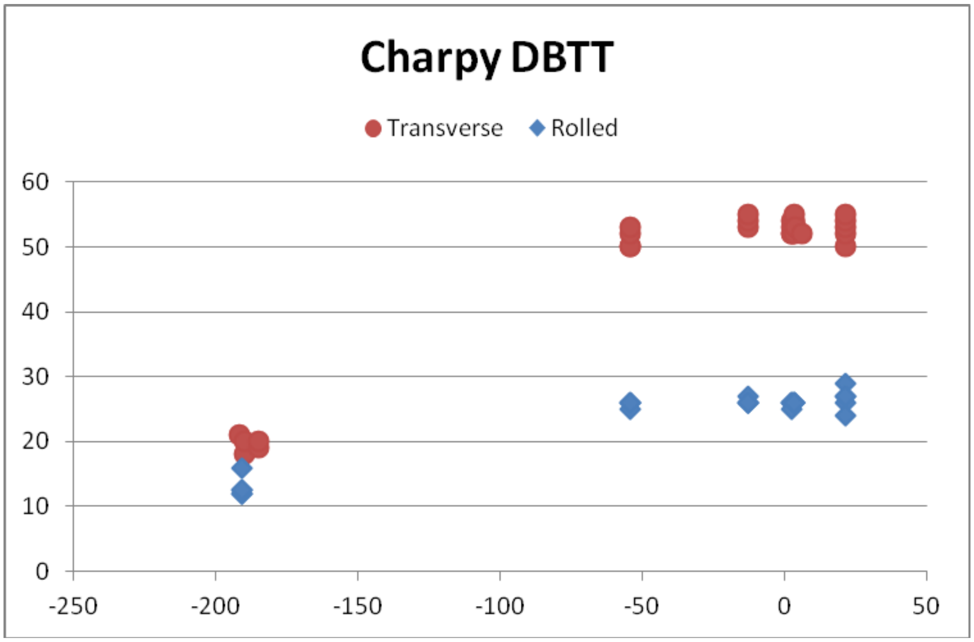


Figure 30. Charpy V-Notch DBTT: Temperature vs. Impact Energy

3. Tensile Testing

Tensile testing was conducted on the base material. The yield strength (~750MPa or ~108ksi) is higher than would be expected for the HY-80 steel (strength of ~550 MPa or ~80ksi) leading one to believe that we may have HY-100 vice HY-80. There is some abnormal data some of the tests. More research is required to determine the cause of the abnormality. Tensile testing on the processed material was not accomplished in this study.

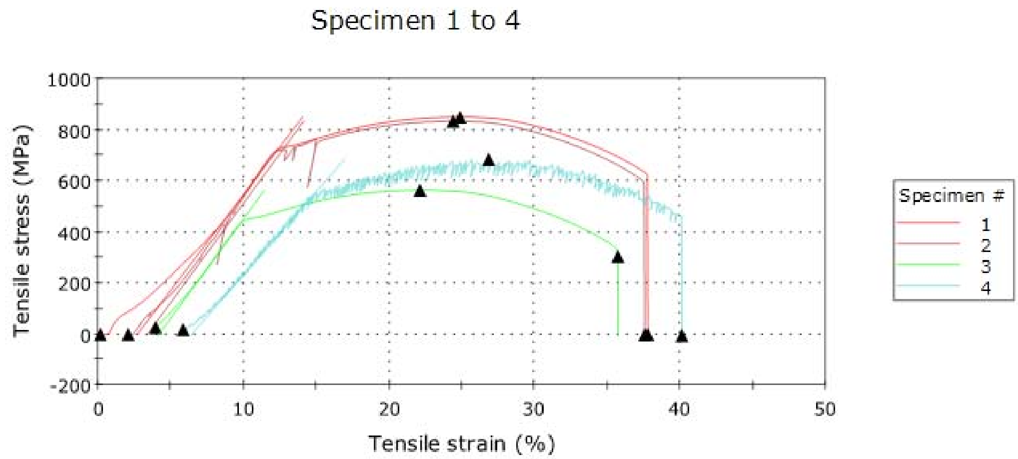


Figure 31. Tensile test with the sample in-line with the rolled direction.

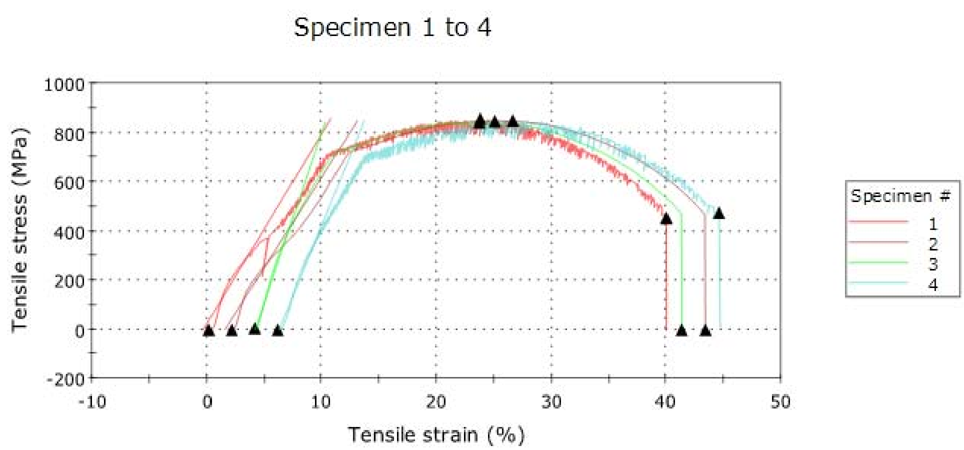


Figure 32. Tensile test with sample transverse to the rolled direction.

V. CONCLUSION

A. SUMMARY OF THIS WORK

In this work, preliminary studies were carried out on the feasibility of underwater FSW of HY-80 steel. In this work. the underwater welding was carried out in 3.5wt% NaCl water .

1. To our knowledge. this forms the first study on feasibility of underwater FSW of HY-80 steel. The feasibility of underwater FSW on HY-80 or 100 has been demonstrated.

2. A non-non tempered martensitic microstructure was formed in the stir zone and this is reflected in a stir zone hardness that exceeds that of the base metal.

3. A defect free weld can be accomplished underwater.

4. Underwater welding of HY-80 or 100 steels in seawater is feasible.

These conclusions show that underwater FSW of HY-80 warrants further research as more questions have been raised than have been answered by this work. The potential cost savings and decreased repair time for the Navy supports further research as well. Further research should focus on the non-tempered martensitic microstructure and how to limit or eliminated it altogether.

B. FUTURE RESEARCH

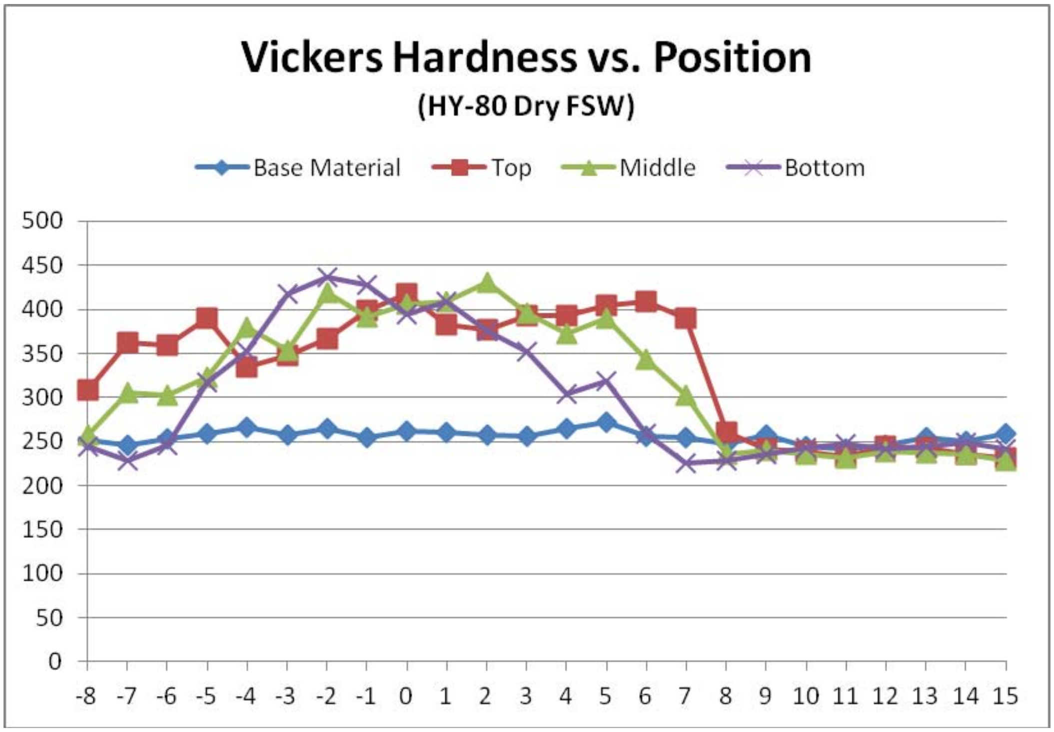
1. The next logical step is conduct similar mechanical property studies on the processed material for comparison as well as hydrogen content analysis of the base material and processed material to ensure no hydrogen embrittlement is occurring.

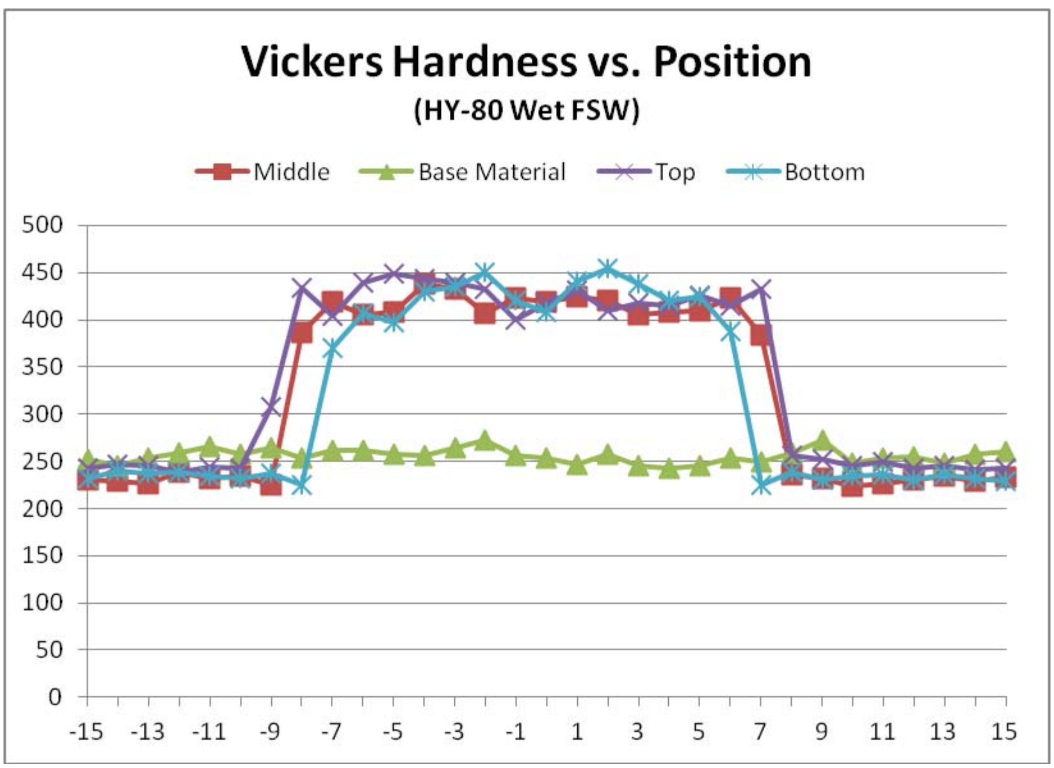
2. The cause of and preventions for the non-tempered martensitic microstructure formation in the stir zone should be evaluated. If this cannot be controlled, the potential for FSW of HY-80 would be limited.

3. A tool test should be conducted to determine the best tool material, and FSW parameters to produce the best results while limiting tool wear.

4. Future material obtained for testing should be requested to include certificates verifying the material.

APPENDIX A – MICROHARDNESS GRAPHS





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APPENDIX B – ANAMET REPORT

LABORATORY CERTIFICATE

Anamet, inc

December 10, 2010

LABORATORY NUMBER: 5004.5217

CUSTOMER AUTHORIZATION: Pay by Credit Card

DATE SUBMITTED: December 2, 2010

REPORT TO: Naval Postgraduate School
Attn: Sarath Menon
700 Dyer Road,
ME Bldg 245
Monterey, CA 93943

SUBJECT:
One coupon was submitted for chemical analysis. The sample was identified as approximately 0.2" thick steel section.

SPECTROCHEMICAL ANALYSIS
(Reported as Wt. %)

Requirements
Ultra Service Steel
USS HY-80

			Min.	Max.
Carbon	(C)	0.167	---	0.18
Chromium	(Cr)	1.52	1.00	1.80
Copper	(Cu)	0.09	---	0.25
Manganese	(Mn)	0.39	0.10	0.40
Molybdenum	(Mo)	0.24	0.20	0.60
Nickel	(Ni)	2.33	2.00	3.25
Phosphorus	(P)	0.015	---	0.025*
Silicon	(Si)	0.24	0.15	0.35
Sulfur	(S)	0.015	---	0.025*
Titanium	(Ti)	<0.005	---	0.02
Vanadium	(V)	0.01	---	0.03

*P + S = 0.045 Max.

The testing was completed on December 3, 2010 and performed in accordance with the customer's authorization. The results meet the listed requirements.

Submitted by:

Edward C. Foreman

Edward A. Foreman
Quality Manager

eaf

26102 Eden Landing Road, Suite 3, Hayward, California 94545-3811 Phone: 510-887-8811 Fax: 510-887-8427 www.anametinc.com

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